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Electro-optical logic gates based on graphene–silicon waveguides

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ABSTRACT

In this paper, designs of electro-optical AND/NAND, OR/ NOR, XOR/XNOR logic gates based on cascaded silicon graphene switches and regular 2×1 multimode interference combiners are presented. Each switch consists of a Mach–Zehnder interferometer in which silicon slot waveguides embedded with graphene flakes are designed for phase shifters. High-speed switching function is achieved by applying an electrical signal to tune the Fermi levels of graphene flakes causing the variation of modal effective index. Calculation results show the crosstalk in the proposed optical switch is lower than -22.9 dB within a bandwidth from 1510 nm to 1600 nm. The designed six electro-optical logic gates with the operation speed of 10 Gbit/s have a minimum extinction ratio of 35.6 dB and a maximum insertion loss of 0.21 dB for transverse electric modes at 1.55 μm.

1. Introduction

With the rapid growth of Internet traffic, it is challenging for bandwidth-limited silicon electronics to meet the demand on data processing [1,2]. Silicon photonics with the advantage of massive parallelism, high bandwidth, and high speed provides a promising approach for computing and processing a tremendous amount of information [3,4]. As a basic unit, silicon-based optical logics have gained increased attention in recent years.

All-optical logic gates using the plasma dispersion effect [5], two-photon absorption (TPA) [6], and four-wave mixing (FWM) [7] have been demonstrated in silicon waveguides. Although they can perform ultrafast speed operations, it is not easy to achieve large-scale integration because strong pumps are needed to induce the nonlinear effects to realize logic functions. Logic gates based on the thermo-optic effect in silicon waveguides suffer from low operation speeds [8,9]. A better alternative would be electro-optically tuned devices. Due to the compact footprint and low power consumption, microring resonator (MRR) is considered as an ideal element to construct electro-optical logic gates. A range of electro-optical logic gates based on silicon MRRs have been demonstrated [10,11]. Nevertheless, they have a limited bandwidth and are sensitive to temperature variations. In contrast, the devices based on Mach–Zehnder interferometers (MZIs) show relatively large optical extinction ratio and broadband operation, but require large footprints [12,13].

Graphene, a two-dimensional material, has the unique and extraordinary electronic and optical properties which make it an attractive option for realizing novel devices, such as gate-variable optical conductivity [14], ultrahigh electron mobility [15], and wideband optical absorption [16]. Plasmonic modes can be supported by the doped graphene. Electro-optical graphene plasmonic logic gates have been designed with a minimum extinction ratio of 15 dB at an operating wavelength of 10 μm [17]. When graphene is combined with the silicon waveguide, the modal effective index of the graphene–silicon waveguide (GSW) varies according to the carrier density in graphene. Previously, Bragg gratings [18], TE-pass polarizers [19], photodetectors [20–22], switches [23], and modulators [16,24] based on GSWs have been reported.

In this paper, 10 Gbit/s electro-optical logic gates for AND/NAND, OR/NOR, and XOR/NXOR operations using cascaded silicon graphene switches based on MZIs (SGMZIs) and 2×1 multimode interference (MMI) combiners are proposed and numerically studied. The variations of the effective indices of guided modes in the phase shifters of SGMZIs are investigated by using finite-difference time-domain (FDTD) simulations. The functionalities and properties of electro-optical logic gates are evaluated and analyzed. These electro-optical logic gates offer the performance merits including large extinction ratio, low insertion loss, high operation speed, and broad bandwidth. Moreover, the dependence of the performance of SGMZI on the dielectric is also discussed.

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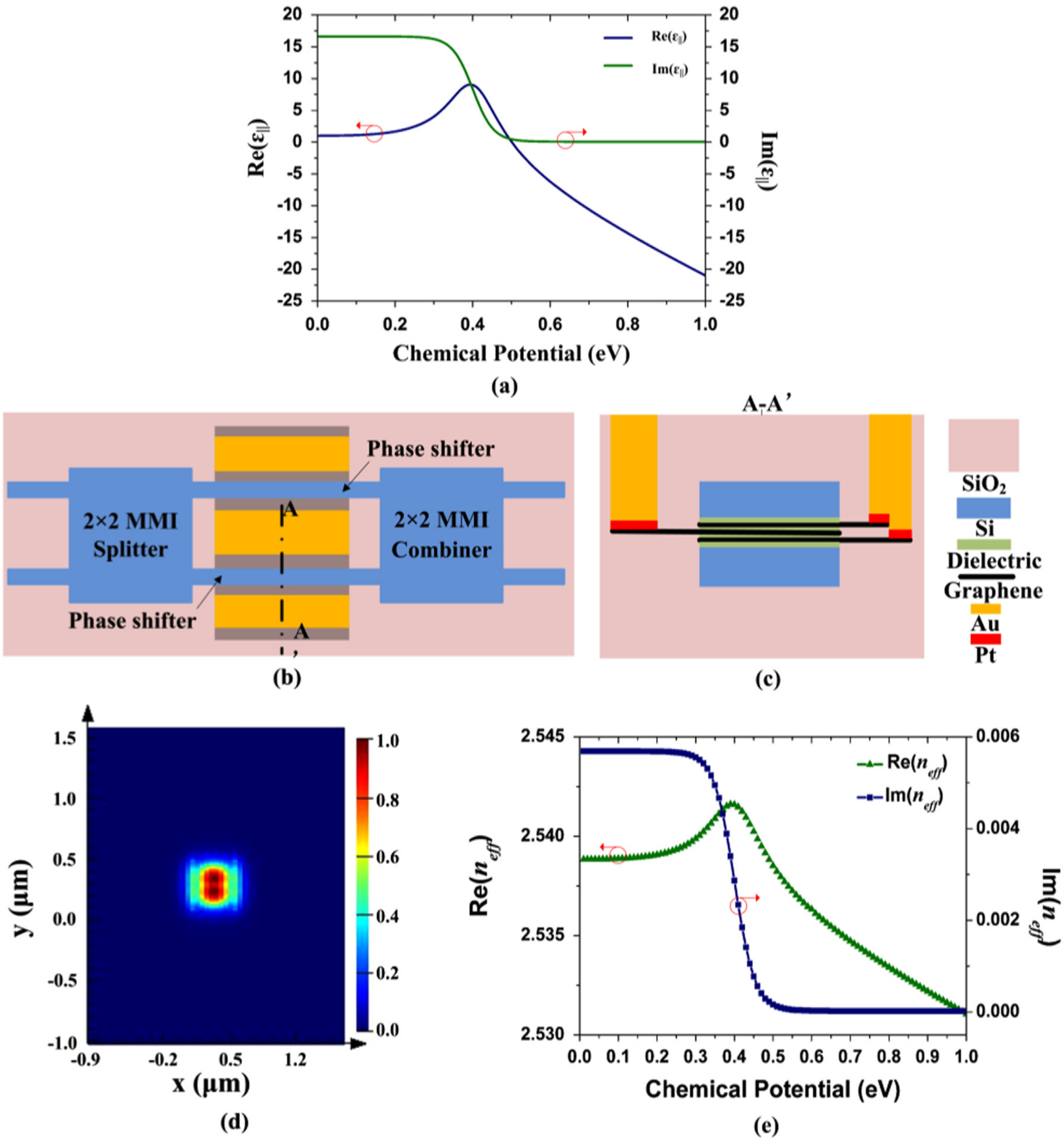

Fig. 1. (a) The in-plane permittivity of graphene as a function of the chemical potential (b) Structure of the 2×2 SGMZI (c) Cross-section of the phase shifter (d) Optical mode profile in the silicon slot waveguide embedded with graphene flakes for the TE mode (e) Effective index in the phase shifter of the SGMZI as a function of the chemical potential.

2. MZI-based silicon graphene switch

2.1. Graphene's conductivity and permittivity

The monolayer graphene is treated as an anisotropic material. The in-plane optical conductivity σ of the monolayer graphene obtained from the Kubo formulas is given by the following equations [25]

$$\sigma = \sigma_{\text{intra}} + \sigma_{\text{inter}} \tag{1}$$

$$\sigma_{\text{intra}} = \frac{-ie^2}{\pi\hbar(\omega + i2\Gamma)}\left[\int_0^\infty \varepsilon\left(\frac{\partial f_d(-\varepsilon)}{\partial\varepsilon} - \frac{\partial f_d(-\varepsilon)}{\partial\varepsilon}\right)d\varepsilon\right] \tag{2}$$

$$\sigma_{\text{inter}} = \frac{-ie^2(\omega + i2\Gamma)}{\pi\hbar^2}\left[\int_0^\infty \frac{f_d(-\varepsilon) - f_d(\varepsilon)}{(\omega + i2\Gamma)^2 - 4(\varepsilon/\hbar)^2}d\varepsilon\right] \tag{3}$$

where e represents the charge of the electron, $\hbar$ is the reduced Planck's constant, ω is angular frequency, $f_d(\varepsilon)$ is the Fermi-Dirac distribution, and $\Gamma=(ev_F^2)/(\mu\mu_c)$ is the scattering rate which is a function of the graphene's carrier mobility μ, the Fermi velocity v_F, and the chemical potential μ_c. The Fermi-Dirac distribution $f_d(\varepsilon)$ is defined as $f_d(\varepsilon) = (e^{(\varepsilon-\mu_c)/k_BT} + 1)^{-1}$, where k_B is the Boltzmann constant and T is temperature.

When the monolayer graphene is treated as an ultra-thin film, the relationship between the in-plane permittivity of the graphene $\varepsilon_\parallel$ and the in-plane optical conductivity σ is as follows [26].

$$\varepsilon_\parallel = 1 + i\frac{\sigma}{\omega\varepsilon_0\Delta} \tag{4}$$

where ε_0 and Δ are the vacuum permittivity and the thickness of the monolayer graphene, respectively.

In the simulation, T=300 K, Δ=0.34 nm, and v_F=9.5×10^5 m/s are considered. Fig. 1(a) shows the dependence of the in-plane permittivity of graphene on the chemical potential at an operating